June 7, 2001

To: Charles Baker

From Charles Bushnell
Jim Irby
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Peter Mioduszewski
Ron Parker
Aldo Pizzuto
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Subject: External Review of FIRE

The above Committee has concluded 3 days of listening to presentations and detail discussions with the Engineering Team of FIRE. While many design details, concerns, comments and recommendations are attached to this letter, we feel ***very strongly*** that the following four points should be made up front for your consideration:

1. The Pre-Conceptual design team has done an outstanding job of looking across the Physics requirements, and investigating a through range of devices that could be considered. The team has created concepts for new machines that can explore most of the critical physics issues in burning plasmas in a facility of modest cost.

2. These Pre-Conceptual investigations have been carried out in amazing detail, considering our observations that the team is less than the required "critical mass" for the proper confrontation of this effort. This has limited their ability to fully address a number of critical engineering problems in detail.

3. It is ***CRITICAL*** that immediate **resources** be provided to raise the team to the required "critical mass" so that it can properly conclude the Pre-Conceptual Design phase in an expeditious and efficient manner.

4. It is also ***CRITICAL*** that immediate **resources** be provided to expeditiously engage in the R&D necessary to support the above design effort.

Attachments: 1.0 Magnet System Summary with summary [associated "chits" at PPPL]
2.0 Vacuum system, PFCs, IRH, Fueling and Pumping Summary with summary [associated "chits" at PPPL]

1.0 Magnet Systems Summary

CRITICAL DESIGN ISSUES:

1. *FOCUS* in an expeditious manner on 2 Designs along the Q = 10 "zone," (not the "Baseline" design) that indicate, at the Pre-Conceptual Design level, an Engineering Margin value in the range of 1.2 to 1.3. This level of margin should also apply to the insulation schemes.

2. Then *FOCUS*, in an expeditious manner on *one* device, either Wedged or Bucked/Wedged (to be selected by the design team.)

3. Incorporated in the focusing effort should also be the *immediate* design attention to the details of leads, both TF and CS, associated cooling fittings and design of all other critical systems that are lacking detail at the Pre-Conceptual level - - See the material below and the associated attached chits.

CRITICAL R&D ISSUES:

1. The qualification of the properties, through R&D of the TF coil Materials (OFHC for the Bucked/Wedged and BeCu for the Wedged device) in sizes and thickness that are representative of those required for fabrication.

2. For either device, the qualification, through R&D, of materials, that are available today, for the insulation systems.

CHIT SUMMARY:

Several committee members were concerned about the copper properties. It is vital that uniform, work hardened properties of the cold rolled thick copper plates or copper alloys for the TF be demonstrated. Issues concerning radiation embrittlement and creep have been mentioned. R&D on the magnet insulation should be continued at a fast pace. Radiation testing in particular is a very time consuming process and should begin as soon as possible. R&D on the weld joints for the TF, and electroforming processes for the CS should be started. Finally, is the bonding process compatible with the copper properties?

Other methods for fabrication of the compression ring should be considered. Nonconductive fiber materials might be used. The jack design needs to be demonstrated as soon as possible. The ring design needs to consider thermal range and stiffness requirements.

The design of the magnet cooling system should be specified, including insulating joints. Both inside and outside cooling channels should be included to reduce between shot cool down times. Cooling between the CS and TF might be considered.

The TF and OH terminal and connections should be analyzed and designed as soon as time permits. These locations have proven to be areas of likely failure and must be part of the early design effort. Moving the TF connection away from the ports might allow for a larger, stronger buildup.

Out-of-plane forces during disruptions need to be considered in the TF design.

The function of the cryostat should be defined. Does it need to be a secondary containment barrier?

Whether or not castings can be used is a major cost issue. R&D on the castings should be done soon so that a realistic costing and design can be done.

A bucked and wedged design should be supported by a detailed assembly and disassembly procedure.

We have concerns about operation at 12T where very costly power supplies, motor generators, and development of new RF heating sources might be required.

2.0 Vacuum System, PFCs, IRH, Fueling and Pumping Summary

CRITICAL DESIGN ISSUES:

1. Divertor heat load. The design divertor heat load of 25 MW/m2for the outer divertor is at the limit of engineering feasibility . There appears to be no margin in the proposed design. Also, if 20% of the power flows to the inner divertor, the pulse length will be limited by the inertial cooling approach. As in the case of the inner divertor there would be very little margin to uncertainties in uniformity and power split.

CRITICAL R&D ISSUES:

1. Behavior of Tungsten rods in divertor plates under disruption conditions (loss of melt layer, effects on neighboring rods, etc.)

DEVELOPMENT AND DESIGN CHOICES: (Less critical, but important)

- Develop a complete description of disruption loads and stresses
- Payload for boom: Likely too high in present design
- Single vs. double null: justification by comparison
- Segmentation of divertor modules
- Design of inner divertor is marginal for expected heat loads and uncertainties. Active cooling?
- Diagnostic design and potentialR&D required

OPTIMIZATION ISSUES

- ITER Structural Design Criteria should be adopted and expanded as necessary.
- Require 10^4 l/s pumping speed (molecular flow).
- Flexibility to handle different operating modes (li, βpol)
- Protection against runaway s
- Cu-SS bonding method for in-vessel use

CHIT SUMMARY:

Divertor/Baffle Heat Loads and Performance

Divertor heat loads do not account for uncertainties in splitting of power between inner and outer divertor, nor in possible toroidal asymmetry. The peak power could be higher than the assumed 25 MW/m^2, which seems already to be at the limit of the design. Power density scaling with respect to machine design variants should be examined. Even a "nominal" power density of 20 MW/m2 leaves too small a margin when toroidal asymmetries are considered. The inner divertor heat handling capacity also leaves too little margin and active cooling may need to be considered.

Charge exchange fluxes at the divertor entrance can be large. Sputtering from the Beryllium tiles can lead to Tungsten sputtering from the divertor targets and result in unacceptable Tungsten levels in the main plasma. More analysis with Monte Carlo neutral modeling should be done to evaluate the erosion.

It is not clear that the short connection lengths in the SOL can support sufficiently high SOL edge T_e to be compatible with requisite pedestal temperature. Study should be done on the relationship of the SOL and pedestal temperatures.

Detached or partially detached divertor operation can substantially lower the peak heat fluxes on the divertor and the possibility of sputtering of the divertor targets. It is not clear why this regime is not accessible to FIRE, although one factor is the short connection length. Another might involve the specific design. These questions should be examined using a suitable divertor modeling code. Such studies should also address issues of plasma performance, He exhaust, Z_{eff} and control of the neutrals.

It is not clear that a double null solution is optimum for FIRE. It would be useful to understand how the choice of a single null divertor would affect the above issues. The benefits of up-down symmetry are recognized, however these can be retained by maintaining a small gap between the two separatricies.

Divertor Structural Analysis

Stresses caused by divertor disruption loads are well beyond allowables, at least for 316 SS. The Inconel solution is recommended only as a last resort. Inconel has problems associated with activation and joining to SS is not trivial. Instead, and assuming loads remain high after refinement of disruption analysis, a smaller divertor module should be considered, e.g., 32 instead of 16. This would also facilitate design of RH boom and eliminate the need for port cutouts in TF magnet. Thermal stresses arising from constraining the fingers need to be urgently examined. Using multilam contacts carrying several kA/cm^2 to reduce currents circulating in the divertor module is risky and should be *discouraged*. This approach has been considered for other high-performance designs such as ITER but not adopted.

Thermal stress analysis and fatigue analysis including creep effects need to be carried out for Copper components. Combined loading conditions and associated stress design criteria need to be identified. It is noted that the temperature of CuCrZr in the divertor would exceed 550° C at 25 MW/m2, a temperature that would result in overaging.

Disruption prediction using neural network methods has had some success in predicting disruptions and is a valuable tool that could be used to deploy mitigation measures. However as pointed out in the presentations disruption prediction by these methods requires many disruptive shots to train the network and even then is not 100% reliable. Therefore while disruption prediction and mitigation measures should be incorporated into the design, they should not be relied on to reduce the number of disruptions anticipated for design purposes.

A method for gripping the divertor modules with remote handling tools has not been developed. It is important to incorporate the RH approach into the design at an early stage. If holes or cutouts in the plasma-facing side of these components are required, the thermal consequences must be carefully examined.

It is recognized that the divertor, first wall and baffle designs are still in an early stage; however in view of their importance and considering their potential as show-stoppers it is recommended that their design and critical R&D be pursued with high priority.

Vacuum Vessel

The vacuum vessel supports have not been fully analyzed for side loads due for example to VDE's or earthquakes. The proposed design solution requires precise fitup and may not be practical. An alternative design using a linkage-type attachment (see for example the ITER design) to the port extensions might be considered.

The preliminary disruption analysis results presented to the Committee were quite impressive and the OPERA software looks to be an extremely valuable tool. It should be used to develop a complete set of vessel as well as divertor disruption loads. So far, the port cutouts have not been included in the model and therefore local stresses caused by interruption of the eddy currents at the ports have not been assessed. These effects as well as the torques induced on the port plugs should be evaluated with some priority. Since the disruption loads are design drivers, a more complete description of the loads and stresses should be developed with some urgency. The effects of the collapse of the diamagnetic current, which is then followed by the collapse of the paramagnetic current, should also be examined.

Taking credit for the Copper in the SS-Cu composite vessel wall to react the primary hoop stress caused by disruptions is questionable and could be challenged by regulators. It would be better if such primary stresses could be held within allowables by considering only the steel. As in the case of the divertor design criteria for combined loading conditions have to be satisfied. Fatigue evaluations are needed for regions of stress concentrations. The tradeoff in terms of vessel stresses between the present design that has shielding inside the vessel, and one in which the shielding is exterior to the vessel might be worth a look.

Pumping and Fueling

The overall pumping speed, both for pumpdown and operation seems to be too low, particularly in the molecular flow regime. A minimum pumping speed of 10^4 l/s is necessary to meet base requirements. This should be achieved in the molecular flow regime. Also there does not appear to be enough room for the cryopumps. It may be possible to improve the pumping situation by expanding the divertor ports as they progress through the magnets and opening them up, for example to a circular cross-section, once they have exited from the magnets. An attempt should be made in the design to exhaust the cryo panels into forepumps rather than into the machine. If infeasible, the large ports should be used.

The vacuum properties of the Cu-SS wall composite are unknown – could there be trapped volumes? Preinstallation inspection methods need to be defined. Fabrication and testing of a sub-scale composite prototype would be worthwhile.

There is a concern regarding the potential for freezing of water in the LN2 environment. Methods of prevention/detection should be considered, e.g., doubly contained piping.

General Comments

Rescue methods for the remote handling boom need to be identified. A second boom seems to be a requirement, at a minimum.

Safety implications of residual LN2 in the cryostat during a shot need to be examined.

A more complete 3-D neutronics analysis that takes account of streaming through penetrations needs to be initiated to ensure that the goal of hands-on maintenance can be achieved.

There are too few shots per day and the between shot dwell time is too long. If TF cooling sets the rep rate, cooling on the inner TF bore might be considered. Also, more full power shots would be desirable. If insulator dose is the issue, adding more inner leg shielding should be looked at.

Diagnostic design and identification of R&D needs is urgently needed. This area is one of generic value to US fusion program.

In general, safety factors consistent with the ASME code should be used. For fusion-specific items, such as high heat flux components and radiation embrittlement, and for fatigue, creep/fatigue and inelastic analysis design rules, the ITER structural design criteria (ISDC) should be used and expanded if necessary for the FIRE design.

Bucked and wedged design is justified by complex, nonlinear, contact stress analysis. The analysis needs to be benchmarked by tests.